Formation of Large (50–100 μm) Ice Crystals Near the Tropical Tropopause: Implications for TTL Water Vapor Concentration

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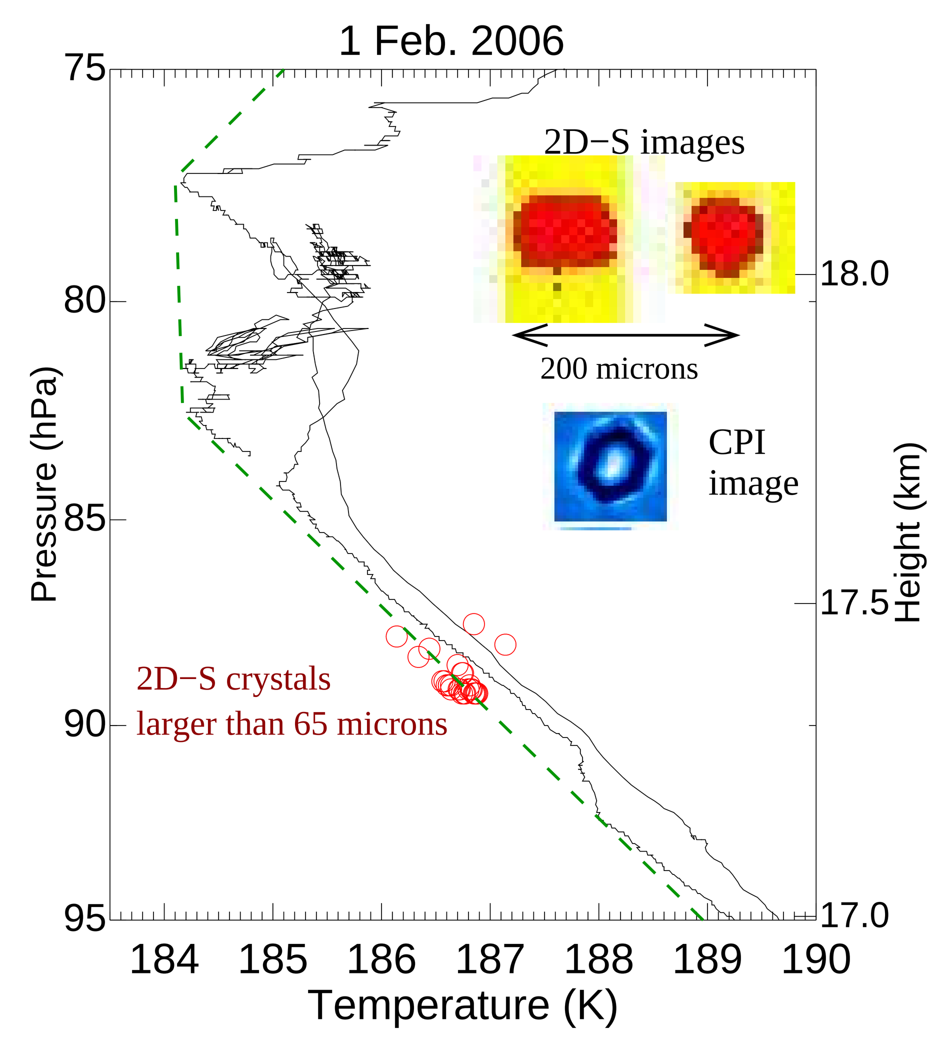
1. Large crystals sampled in the TTL during CRAVE



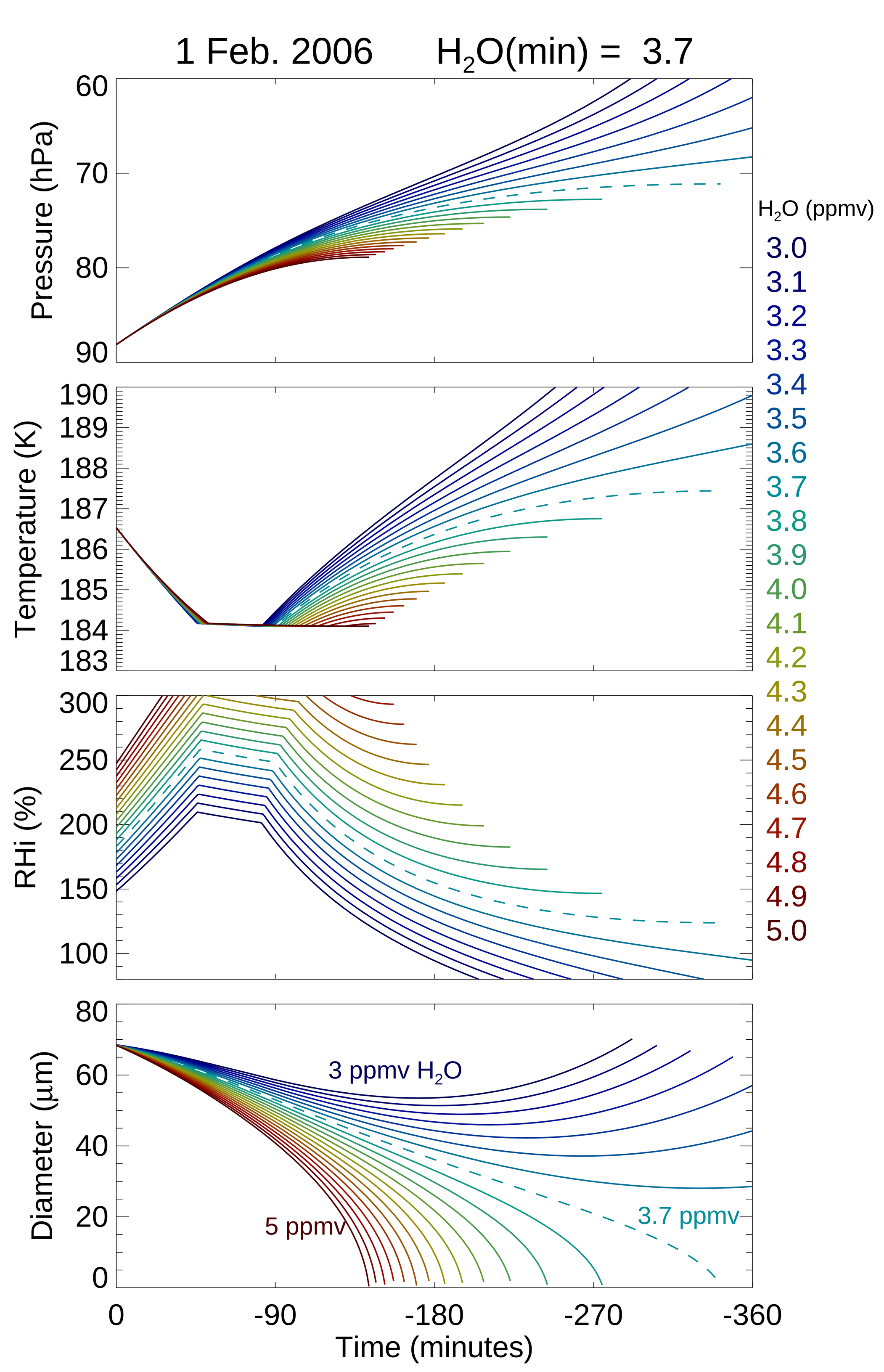
- Large ($D_{eq} > 65$ μm) were detected with all three microphysics instruments (CPI, 2D-S, and CAPS).
- The large crystals were not left over from convection or formed by aggregation. i.e., they must have grown in situ in the TTL.

2. Factors controlling crystal growth

Issue	Assumption	Impact on crystal growth
Upstream T-prof	Weak stratospheric lapse rate	Deeper supersaturated layer
Deposition coefficient	Unity	Fastest possible growth
Nucleation threshold	RHi = 100%	Deepest supersat. layer
Crystal temperature	$T_{ice} = T_{amb}$	Fastest growth
Ice phase (cubic/hexagonal)	Hexagonal	Fastest growth
Crystal habit	Oriented plate	Minimum volume, slow sedimentation

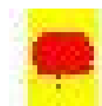
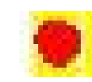
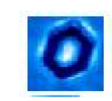
- Assumptions are made that maximize crystal growth rates and minimize H_2O concentration required to grow the crystals.

3. Reverse-time crystal growth-sedimentation simulations



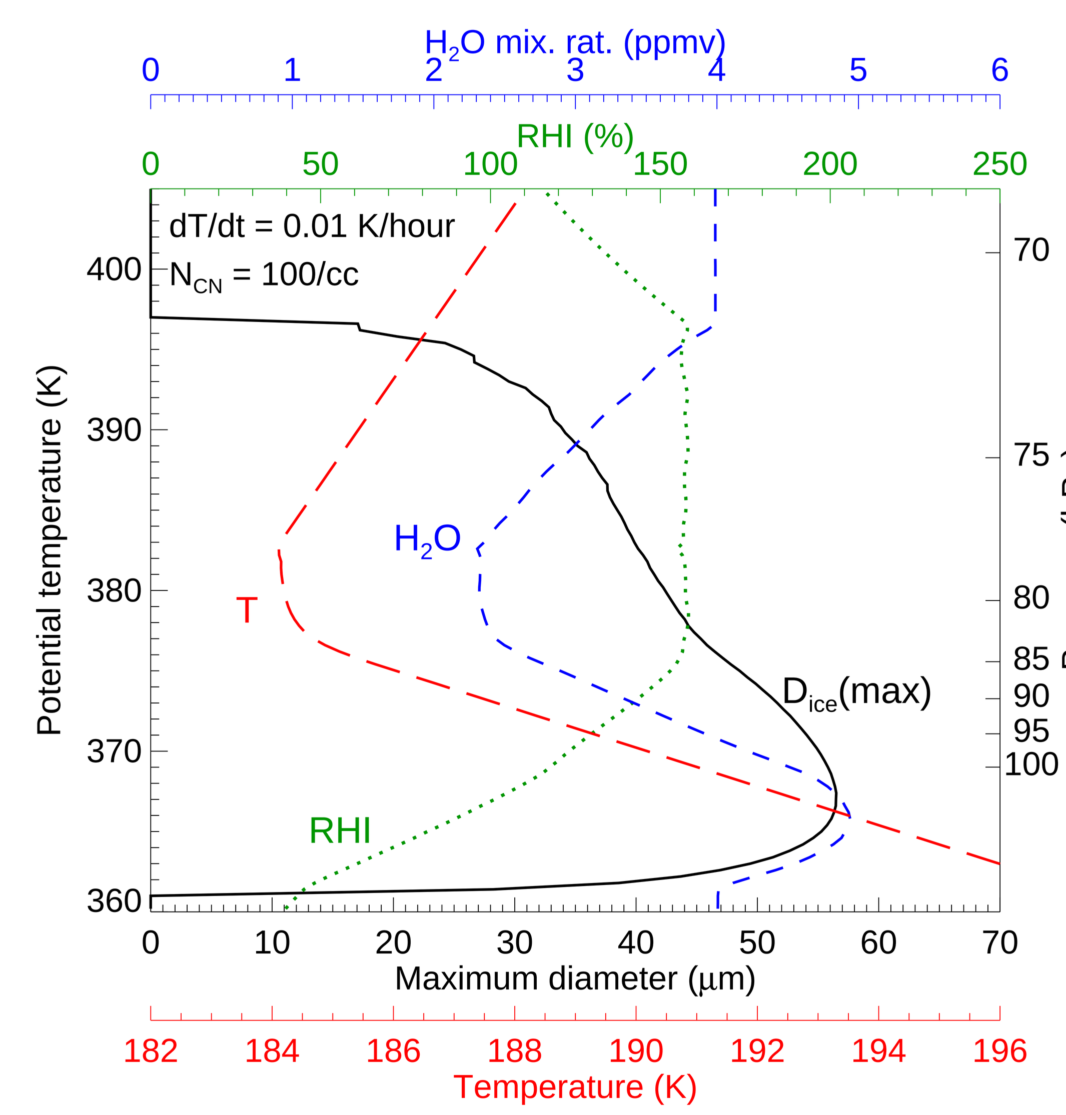
- Formation of large crystal detected by CPI can only be explained if the TTL water vapor concentration is at least $\simeq$3.7 ppmv.

4. Results for in-focus crystals

Image	Pressure (hPa)	D_{eq} (μm)	H_2O_{thresh} (ppmv)
	89.1	75.7	4.0
	89.1	71.5	3.6
	87.9	68.6	3.7

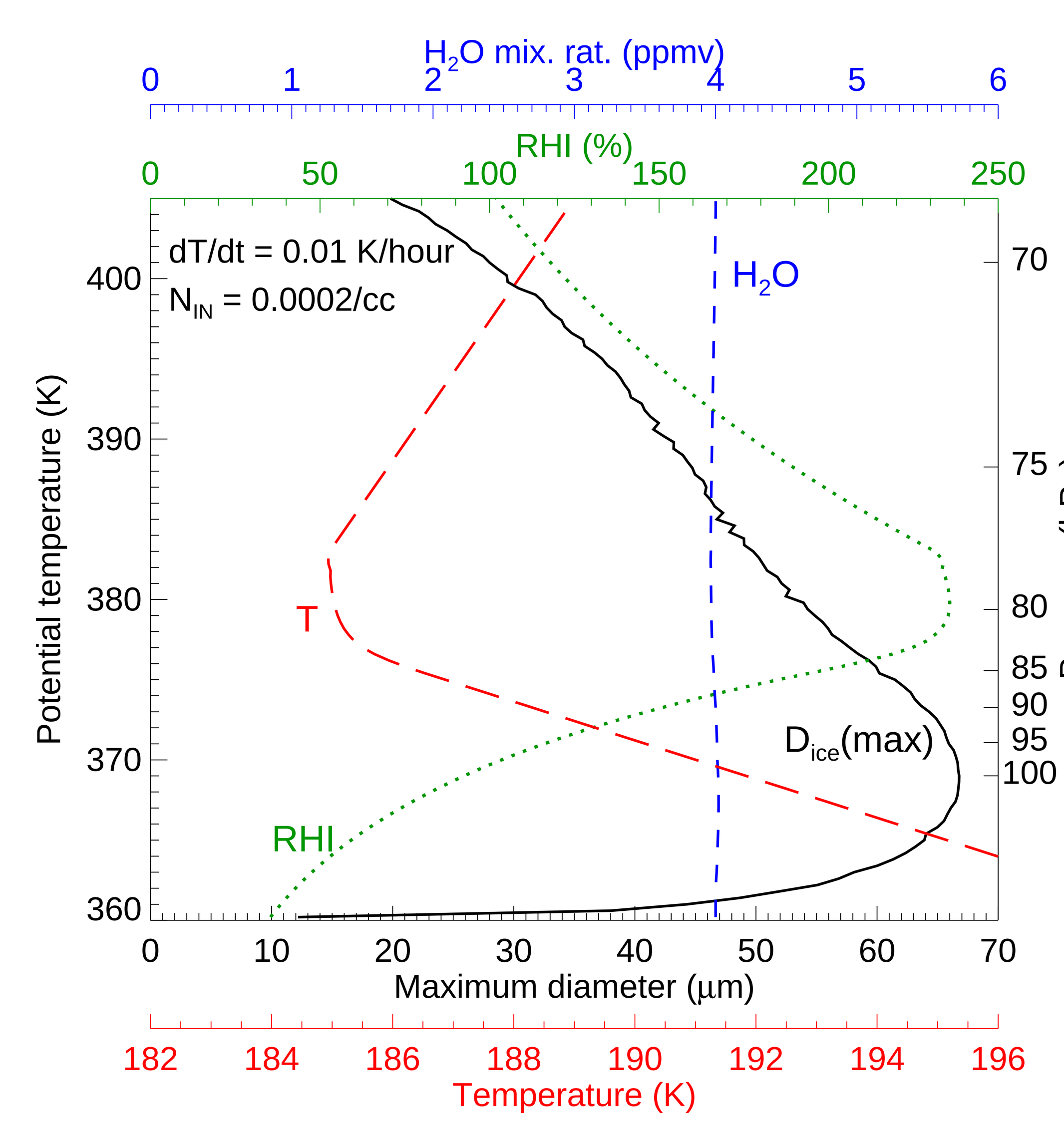
- With ideal amplitude, frequency, and phase, gravity wave temperature and wind perturbations reduce the threshold H_2O concentration from about 4 ppmv to 3.7 ppmv.

5. 1-Dimensional cloud simulation with slow cooling



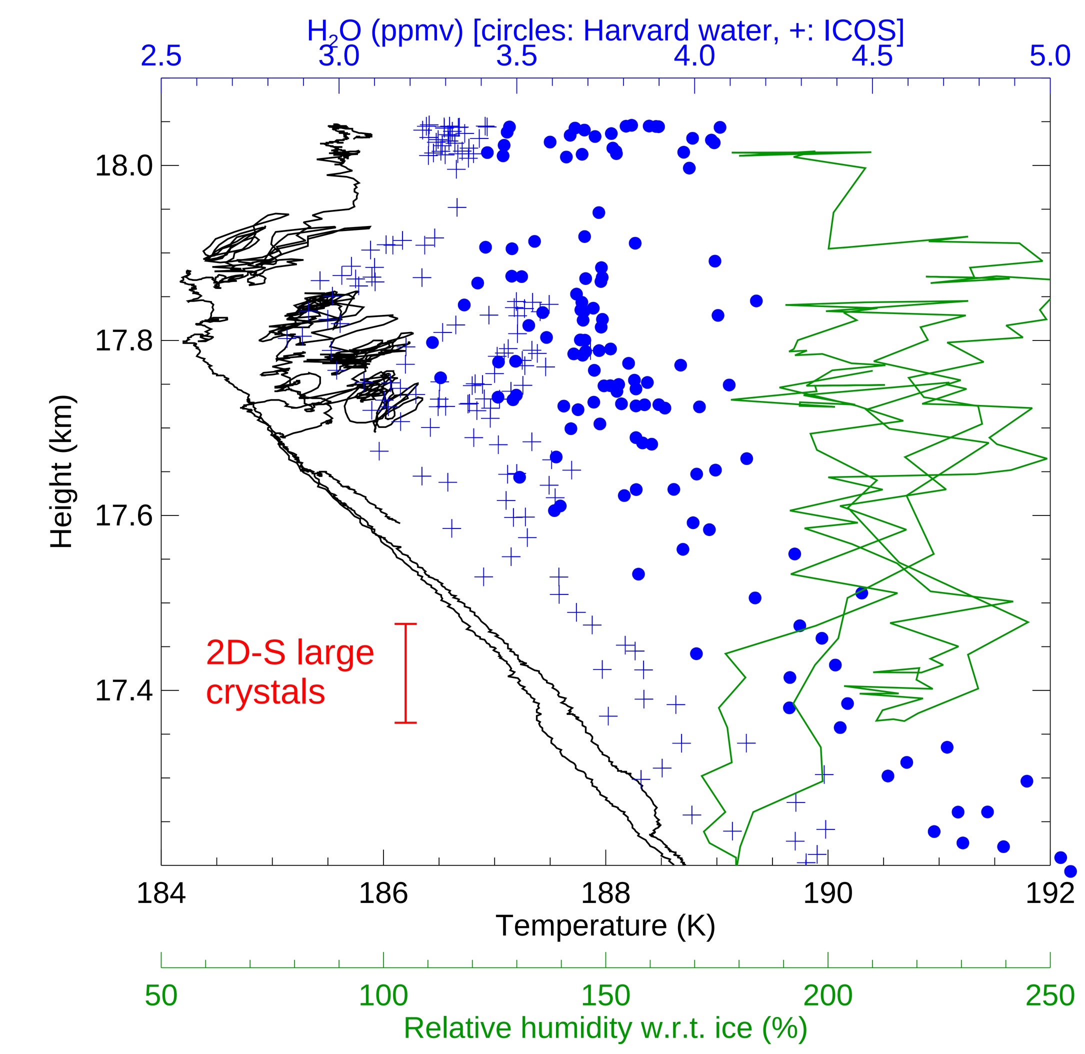
- With standard nucleation schemes, even with very slow cooling, enough ice crystals nucleate to deplete the vapor and prevent the crystals from growing as large as those observed.

6. Cloud simulation with sparse effective ice nuclei



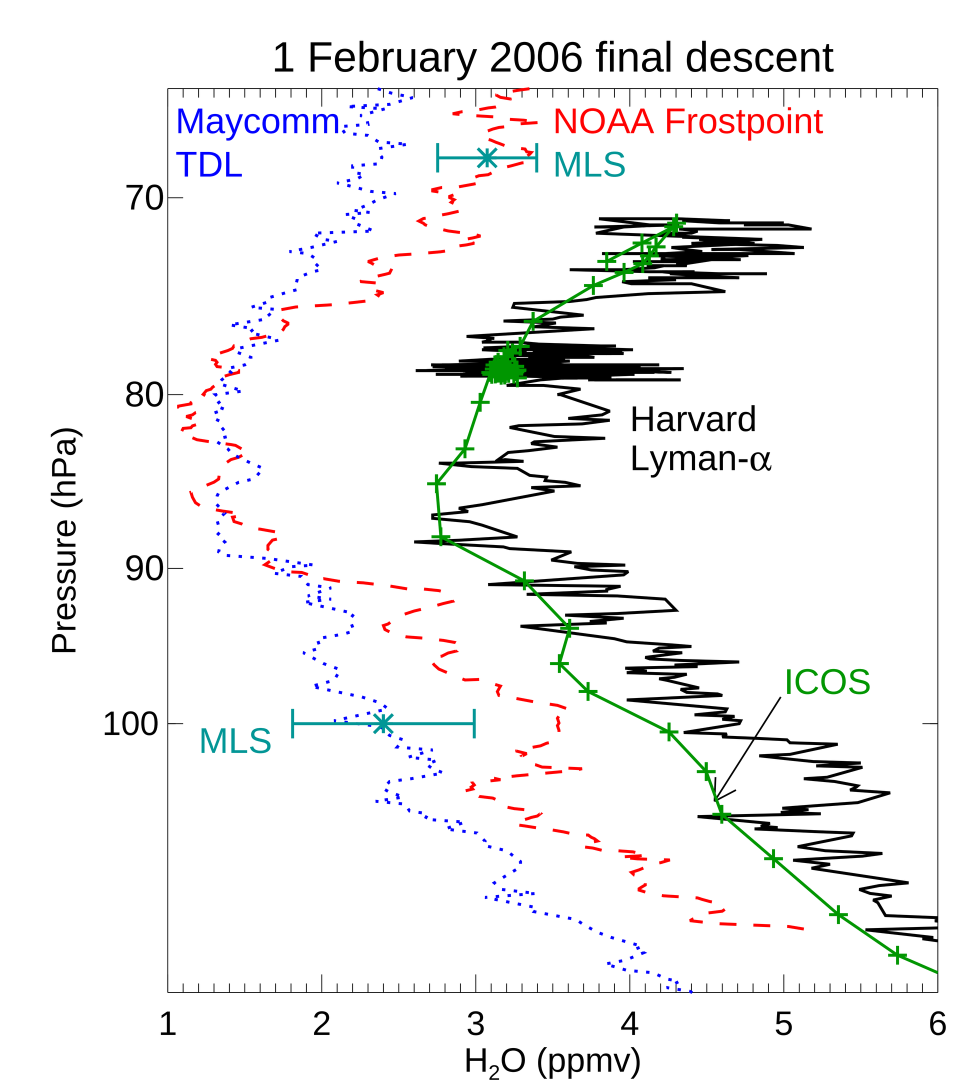
- We can only explain the large-crystal formation if a very small concentration (< 1 L^{-1}) of effective ice nuclei are present and the vast majority of aerosols do not nucleate ice even at high supersaturations.

7. Water vapor measurements during TTL cirrus sampling



- ICOS and Harvard water measurements indicate 3–4 ppmv in the TTL during the cirrus sampling time period.
- The aircraft measurements are consistent with the H_2O thresholds required to grow the large crystals.

8. Sonde/aircraft water vapor measurement discrepancy



- The NOAA frostpoint and Maycomm TDL sondes systematically reported 1–2 ppmv less water in the TTL than the aircraft instruments.
- MLS v. 1.5 H_2O retrievals in the vicinity of the CRAVE measurements are in agreement with the sondes.

9. Summary

- Water vapor concentrations in the tropopause region ($\simeq$17.4–18.4 km) must have been at least about 3.3–3.7 ppmv to grow the large crystals. The corresponding ice relative humidity is very large ($\simeq$200–250%).
- A small number (< 0.5 L^{-1}) of effective ice nuclei must have allowed nucleation of the crystals at relatively low supersaturations.
- Ice nucleation must not have occurred on the vast majority of aerosols even at very large supersaturations.

10. Implications

- The large-crystal growth simulations imply that the WB-57 water vapor measurements are correct.
- Large ice supersaturations can persist in TTL cirrus (contrary to recent modeling study assumptions).
- TTL cirrus do not, by any means, dehydrate air down to ice saturation.